Latest Higgs results from ATLAS

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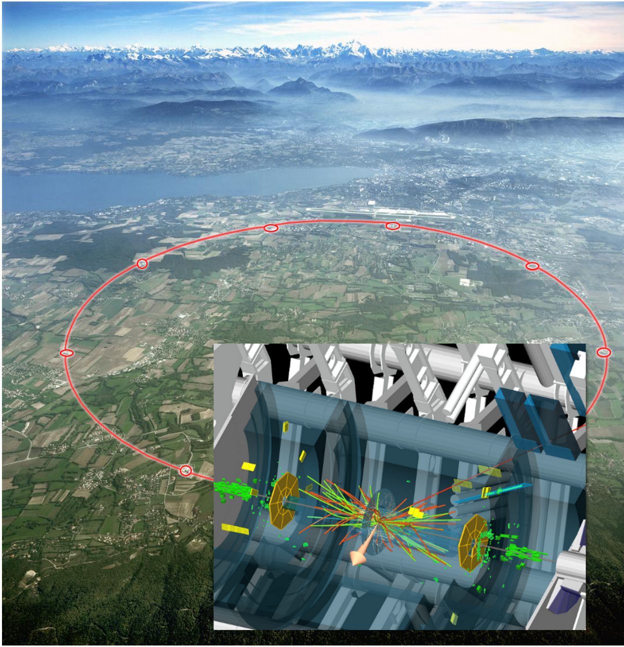
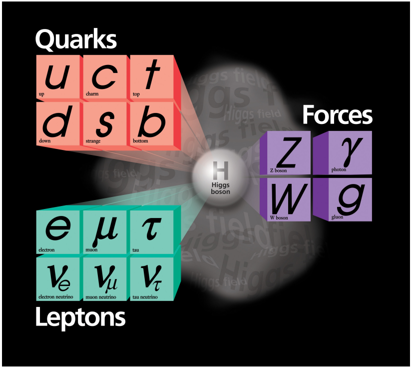
October 5, 2012

- Overview
- ATLAS experiment
- $H \to WW$
- Combined results
- Higgs properties
- Future outlook



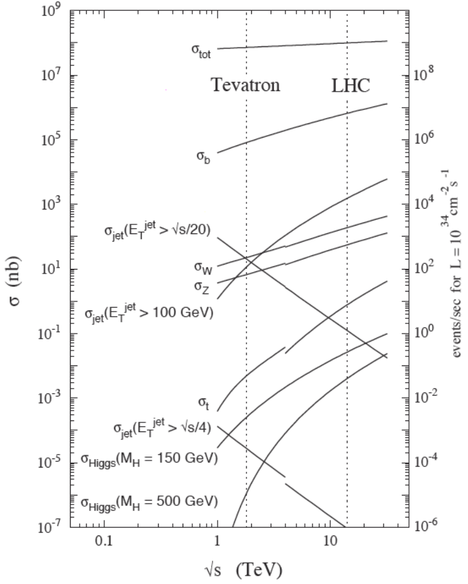
The Standard Model

- The Standard Model is a quantum field theory of point-like fermions with interactions mediated by vector gauge bosons
- A very successful description of high energy particle interactions
- $SU(3) \times SU(2) \times U(1)$ gauge theory
- $SU(2) \times U(1)$ is spontaneously broken by a scalar field with non-zero vacuum expectation value
- Predicts a neutral scalar particle: the Higgs boson
- Mass of the Higgs boson is a free parameter in the SM

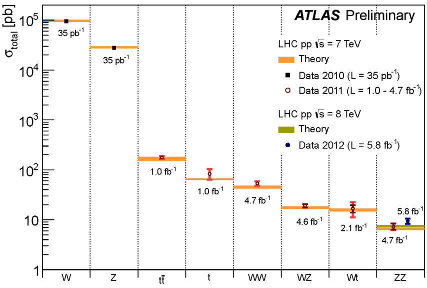


Searching for the Higgs boson is one
of the highlights of the LHC physics program

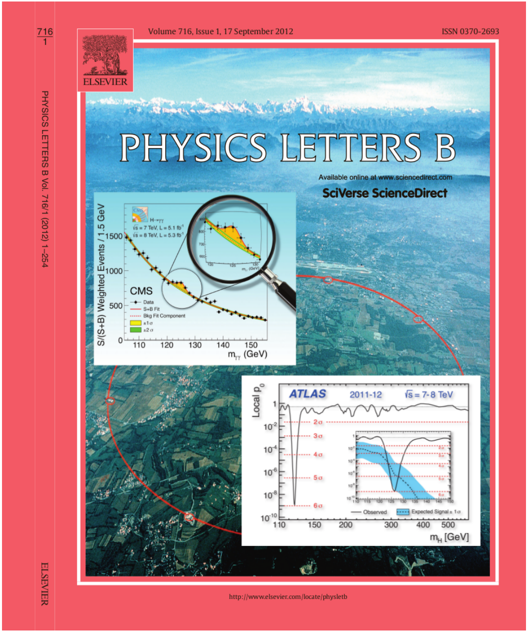
The Standard Model at LHC



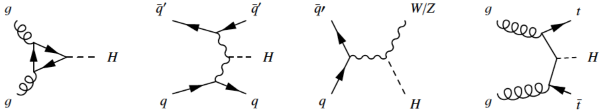
- Precise theory calculations and experimental measurements to test the SM predictions
- Good training for complex Higgs final states (and other searches)



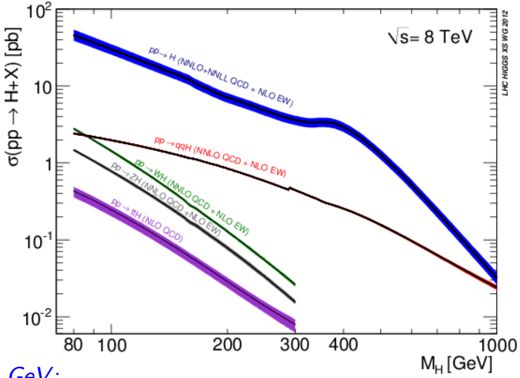
The discovery of a new mass resonance at LHC: $m \approx 125 - 126\ GeV$



Higgs production



arXiv:1101.0593



- Gluon-gluon fusion (ggF)
  - POWHEG+PYTHIA
  - p_T with HqT v2.0
- Vector boson fusion (VBF)
  - POWHEG+PYTHIA
- Associated production:
  - WH/ZH
  - $t\bar{t}$H
  - PYTHIA
- Mass line shape uncertainty:
  - $(150\%) \times (\frac{m_H}{TeV})^3$

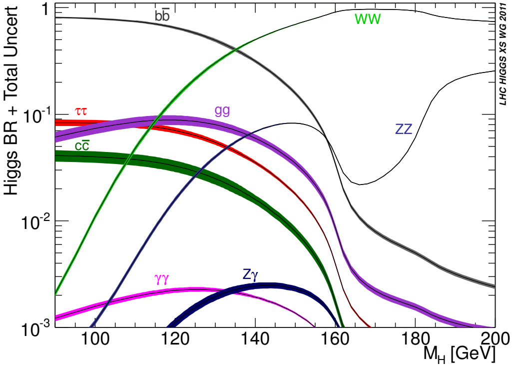
Theory uncertainties for $m_H = 125\ GeV$:

	ggF	VBF	WH/ZH	$t\bar{t}$H
QCD scale	$+7\%\ \ -8\%$	$\pm1\%$	$\pm1\%$	$+4\%\ \ -9\%$
PDF+α_S	$\pm8\%$	$\pm4\%$	$\pm4\%$	$\pm8\%$

Higgs decays

arXiv:1101.0593

- Higgs couplings depend on particle mass
- WW and ZZ dominate when kinematically allowed
- Many competing channels for $m_H < 160$ GeV observable at LHC
- BR for $m_H = 125\ GeV$:
  $\Gamma_H = 4.1\ MeV \pm 4\%$
  $B(H \to \gamma\gamma) = 2.3 \times 10^{-3} \pm 5\%$
  $B(H \to Z\gamma) = 1.5 \times 10^{-3} \pm 10\%$
  $B(H \to \mu\mu) = 2.2 \times 10^{-4} \pm 6\%$



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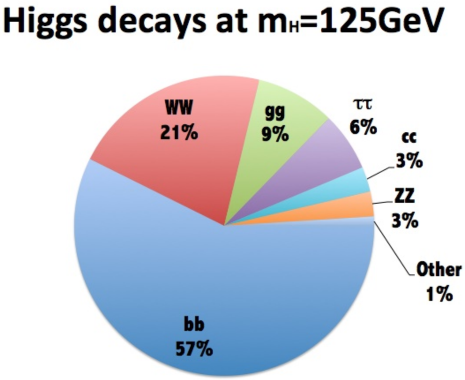


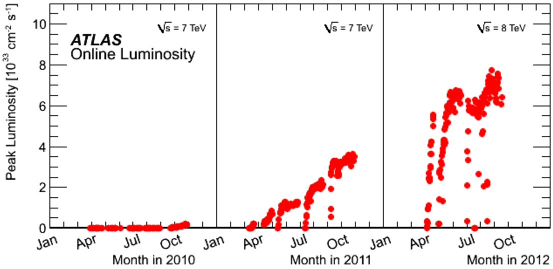
Aidan Randle-Conde

More than 3000 scientists from 38 countries

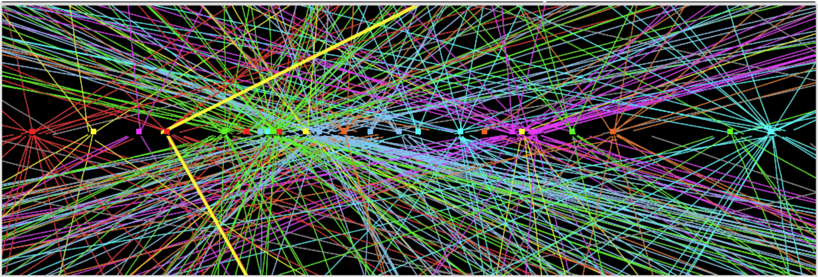
A champagne toast for the discovery


BR 823LW
TWINGO
1768YX01

2012 record instantaneous luminosity: $7.73 \times 10^{33} cm^{-2} s^{-1}$

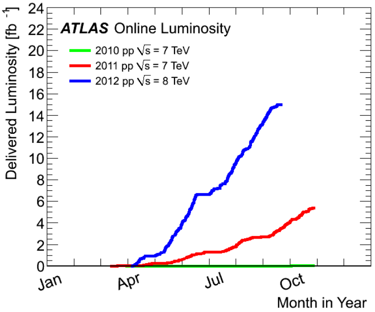


$Z \to \mu\mu$ with 25 vertexes



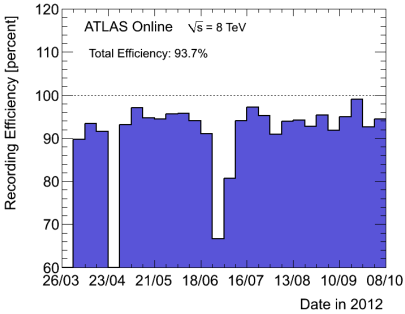
ATLAS experiment

- Recorded $\int \mathcal{L} = 15\ fb^{-1}$ at 8 TeV
- ATLAS is 93.7% efficient during stable LHC collisions
- Recording rate $\approx 500\ Hz$
  - Electron $p_T > 24\ GeV$: $110\ Hz$
  - Muons $p_T > 24\ GeV$: $70\ Hz$
  - Di-photons $p_T > 35, 25\ GeV$: $15\ Hz$

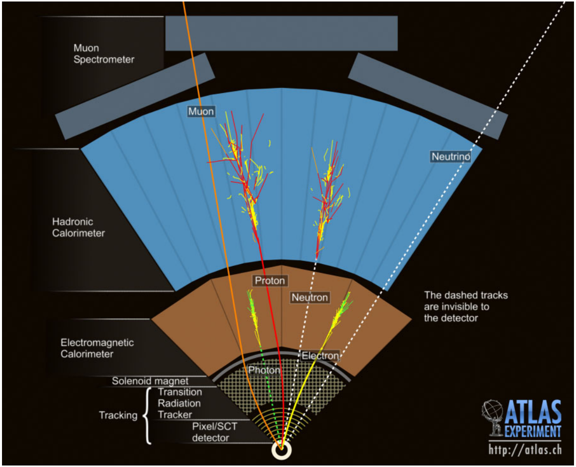


LHC peak luminosity in 2012:

- $\mathcal{L}_{peak} \approx 7.73 \times 10^{33} cm^{-2} s^{-1}$
- pp inelastic $\approx 450\ MHz$
- $Z \to \mu\mu \approx 6\ Hz$
- $gg \to H[125\ GeV] \approx 0.17\ Hz \approx 600/hour$
- $gg \to H[125\ GeV] \to WW \to l\nu l\nu \approx 0.0018\ Hz$

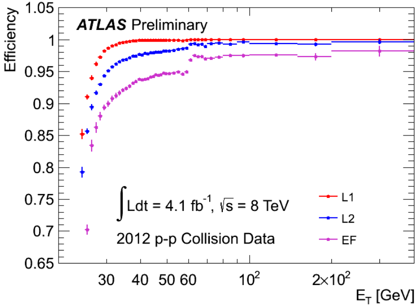


- Precision silicon tracking detectors and Transition Radiation Tracker
- Electromagnetic calorimeter for electron/photon identification and energy measurement
- Hadronic calorimeter for jet energy measurement
- Hermetic design for missing transverse energy measurements
- Muon detectors with air-core toroids

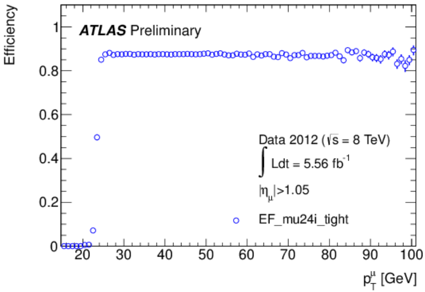


Single lepton triggers

- Single isolated electron trigger with $p_T > 24\ GeV$
- Match Inner Detector track to calorimeter cluster
- Shower shapes for electron and photon id
- Acceptance $|\eta| < 2.5$ and efficiency 90%

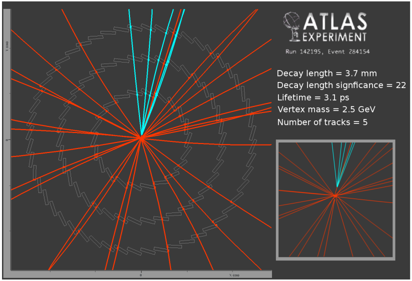


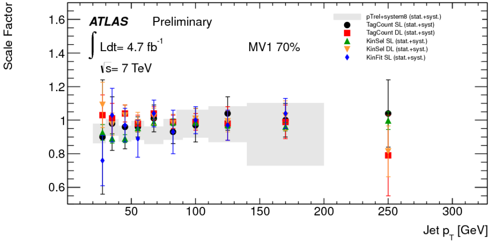
- Single isolated muon trigger with $p_T > 24\ GeV$
- Match Muon Spectrometer track to Inner Detector track
- Trigger acceptance $|\eta| < 2.4$
- Trigger efficiency: 90% in endcap and 70% in barrel (geometric coverage of muon trigger chambers)
- Di-muon efficiency $> 95\%$



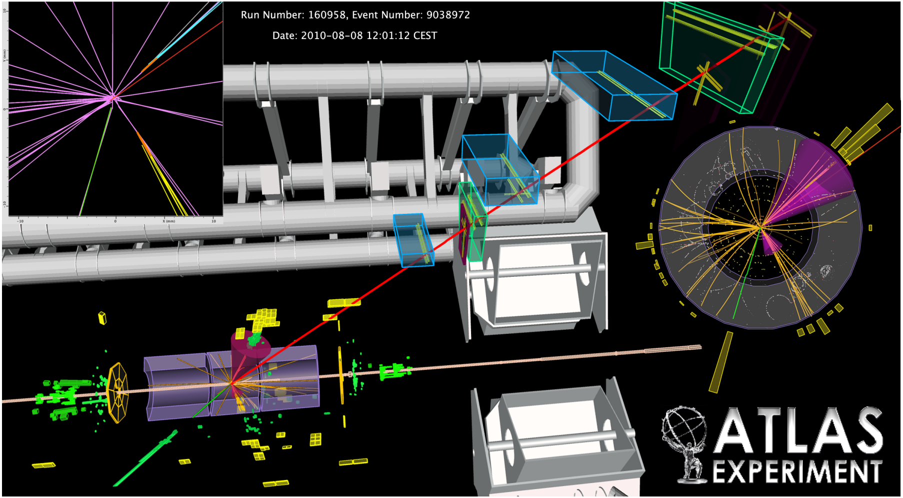
Heavy flavor tagging

- Tag b-quark jets using relative long lifetime of b-hadrons: $c\tau \sim 450\mu m$
- Construct a single (multi-variate) discriminant using impact parameter of tracks inside a jet and secondary vertexes
- A number of btagging algorithms with different working points
- MV1: b-tagging efficiency 85%, light jet tagging rate 11%
- Uncertainty varies between 5% and 18% as a function of jet p_T





$t\bar{t} \rightarrow WbWb \rightarrow e\nu\mu\nu + 2$ b-jets



Higgs results from ATLAS

- Combination of 15 channels with 12 channels used for low mass Higgs
- $\approx$ 100 sub-channels
- Blinded searches for 2012 analyzes
- The ATLAS discovery results presented by Jianming Qian on July 9
- Focus on $H \to WW$ 8 TeV data with $\mathcal{L} = 5.8\ fb^{-1}$ and Higgs properties measurements

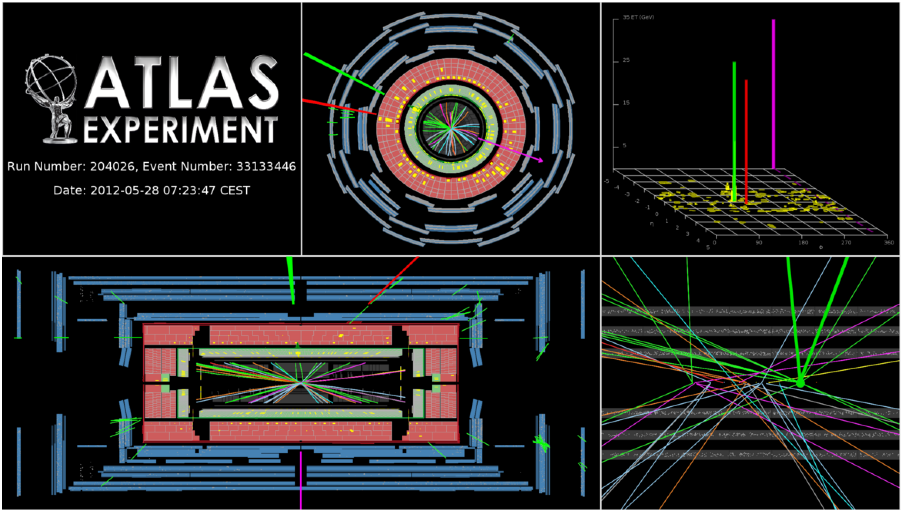
Table 6: Summary of the individual channels entering the combination. The transition points between separately optimised m_H regions are indicated where applicable. In channels sensitive to associated production of the Higgs boson, V indicates a W or Z boson. The symbols $\otimes$ and $\oplus$ represent direct products and sums over sets of selection requirements, respectively.

	Higgs Boson Decay	Subsequent Decay	Sub-Channels	m_H Range [GeV]	$\int L\,dt$ [fb^{-1}]	Ref.
			2011 $\sqrt{s}$ =7 TeV			
2011	$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	110–600	4.8	[87]
		$\ell\ell\nu\nu$	$\{ee, \mu\mu\} \otimes$ {low, high pile-up}	200–280–600	4.7	[125]
		$\ell\ell qq$	{b-tagged, untagged}	200–300–600	4.7	[126]
	$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus$ {2-jet}	110–150	4.8	[127]
	$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu/\mu e, \mu\mu\} \otimes$ {0-jet, 1-jet, 2-jet} $\otimes$ {low, high pile-up}	110–200–300–600	4.7	[106]
		$\ell\nu qq'$	$\{e, \mu\} \otimes$ {0-jet, 1-jet, 2-jet}	300–600	4.7	[128]
	$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes$ {0-jet} $\oplus \{\ell\ell\} \otimes$ {1-jet, 2-jet, VH}	110–150	4.7	[129]
		$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes$ {0-jet} $\otimes \{E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} \geq 20$ GeV$\}$ $\oplus \{e, \mu\} \otimes$ {1-jet} $\oplus \{\ell\} \otimes$ {2-jet}	110–150	4.7	
		$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	{1-jet}	110–150	4.7	
	$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\}$	110–130	4.6	[130]
		$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-200, \geq 200$ GeV$\}$	110–130	4.7	
		$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-200, \geq 200$ GeV$\}$	110–130	4.7	
			2012 $\sqrt{s}$ =8 TeV			
2012	$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	110–600	5.8	[87]
	$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus$ {2-jet}	110–150	5.9	[127]
	$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes$ {0-jet, 1-jet, 2-jet}	110–200	5.8	[131]

$H \to WW \to e\nu\mu\nu$

$m_H = 125\ GeV$: $\sigma \times BR(H \to WW \to l\nu l\nu) = 22.3\ pb \times 0.0106 = 0.24\ pb$

≈ 236 events/ fb^{-1} - a large production rate but difficult and diverse backgrounds



$H \to WW \to e\nu\mu\nu$: analysis strategy

Analysis strategy:

- $H \to WW \to 4q$: 46%
  - large multi-jet backgrounds
- $H \to WW \to l\nu qq$: 44%
  - high mass channel
- $H \to WW \to l\nu l\nu$: 10%
  - High rate, clean final state
  - No mass peak because of ν

Irreducible background:

- WW

Mis-reconstructed backgrounds:

- top: $t\bar{t}, tW, tb, tqb$
- W+jets
- Z+jets
- Di-bosons: WZ, ZZ, W$\gamma^{(*)}$

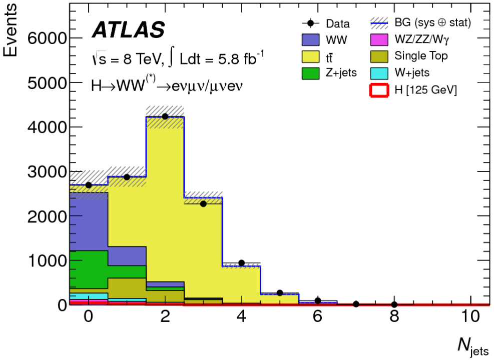
Selection:

- Two isolated opposite sign electron or muon ($p_T > 25, 15\ GeV$)
- Match leptons and jets to common vertex
- Significant missing transverse energy ($E^{rel}_{T,miss} > 25$) not aligned with selected objects
- Separate analysis categories: $(e\mu) \otimes$ (0-jet, 1-jet, 2-jet)
- Large Drell-Yan background for ee and $\mu\mu$ - only $e\mu$ is considered

$H \to WW \to l\nu l\nu$: jet multiplicity

Split by jet multiplicity:

- 0-jet: ggF vs. SM WW
  $\pm 17\%$ for $\sigma_{ggF}(m_H = 125\ GeV)$
- 1-jet: ggF vs. SM WW and top
  $\pm 36\%$ for $\sigma_{ggF}(m_H = 125\ GeV)$
- 2-jet: VBF vs. SM WW and top
  $\pm 4\%$ for $\sigma_{VBF}(m_H = 125\ GeV)$

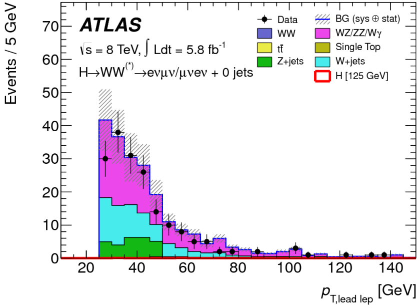


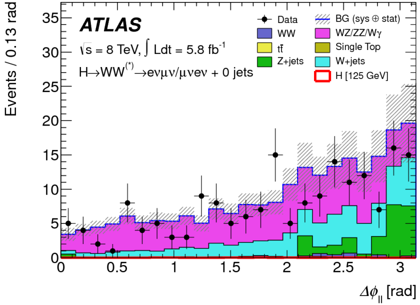
Main detector uncertainties:

- Jet energy scale: $2-9\%$ as a function of jet p_T and η
- Jet energy from pileup: $< 5\%$ for jet $p_T > 25$ GeV
- B-tagging: $5-18\%$ as a function of jet p_T

$H \to WW \to l\nu l\nu$: W+jet, WZ, ZZ, Wγ backgrounds

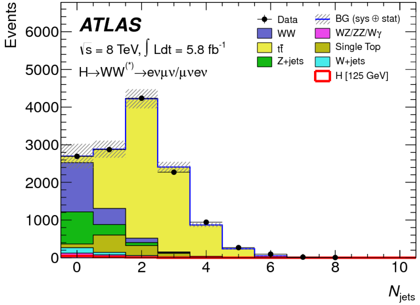
- W+jet background:
  - Jets reconstructed as electrons
  - b-hadron decays to leptons
  - Suppress with tight lepton isolation and particle id (PID)
  - Estimate using events with loosened selection:
    - 40% uncertainty for W+electrons
    - 60% uncertainty for W+muons
- $WZ^{(*)}$ and $Z^{(*)}Z^{(*)}$ backgrounds:
  - One or more leptons are not reconstructed
  - Estimated with simulation
- W$\gamma^{(*)}$ background:
  - Electron from photon conversion
  - Leptons from internal conversions
  - Estimated with simulation
- Same sign di-lepton validation region
  - Observed events: 182
  - Expected events: 216 ± 7 (stat) ± 42 (syst)

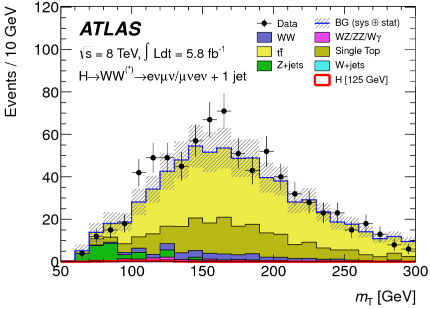




$H \to WW \to l\nu l\nu$: top backgrounds

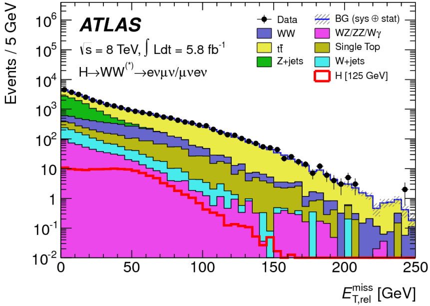
- Top backgrounds in 0-jet:
  - Correct for top b-jet reconstruction
  - Scale MC prediction: 1.11 ± 0.06 (stat)
  - $\sigma = 17\%$
- Top backgrounds in 1-jet and 2-jet:
  - Estimated from control regions that require b-jet
  - 1-jet: 1.11 ± 0.05 (stat), $\sigma = 36\%$
  - 2-jet: 1.05 ± 0.01 (stat), $\sigma = 70\%$



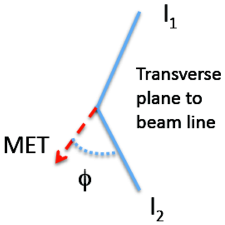


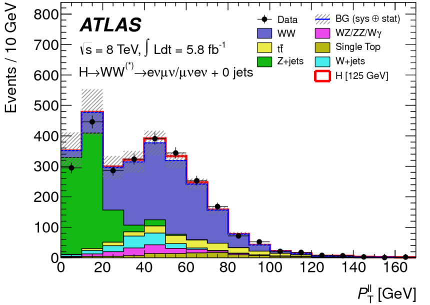
$H \to WW \to l\nu l\nu$: Drell-Yan background

- Drell-Yan (DY) process has no neutrinos in the final state
- Suppressed by requiring significant $E_{T,miss}$
- Pileup events deposit add energy in calorimeters giving fake $E_{T,miss}$
- Only only $e\mu$ final states are included
- $Z/\gamma^* \to \tau\tau$ plus leptonic τ decays
- 0-jet: $p_{T,ll} > 30\ GeV$
- 1-jet: $m_{\tau\tau}$ veto



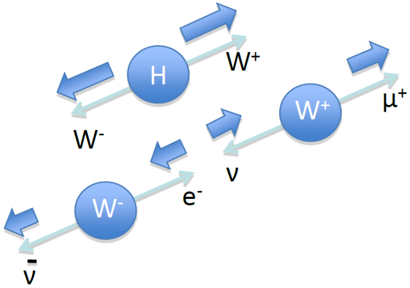
E_{rel}^{miss}=MET
If closest object within 90º,
E_{rel}^{miss}=MET sin ϕ

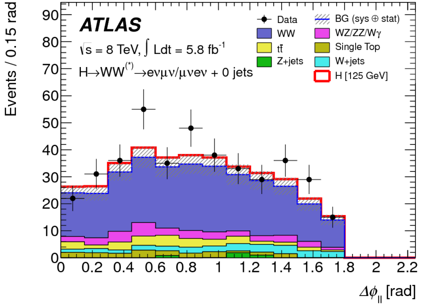


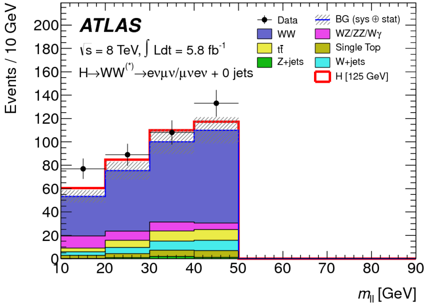


$H \to WW \to l\nu l\nu$: SM WW background

- Largest background
- $H \to WW \to l\nu l\nu$: $\sigma \times BR = 0.237\ pb$
- $qq \to WW \to l\nu l\nu$: $\sigma \times BR = 54.4\ pb$
  - Assuming Higgs is spin 0 particle, spin correlations for WW result in small opening angle for two charged leptons
  - $|m_{ll}| < 50\ GeV$
  - $|\Delta\phi_{ll}| < 1.8$
- Estimate from control regions $m_{ll} > 80\ GeV$
  - 0-jet: 1.06 ± 0.06 (stat), $\sigma = 13\%$
  - 1-jet: 0.99 ± 0.15 (stat), $\sigma = 42\%$







$H \to WW \to l\nu l\nu$: SM WW background

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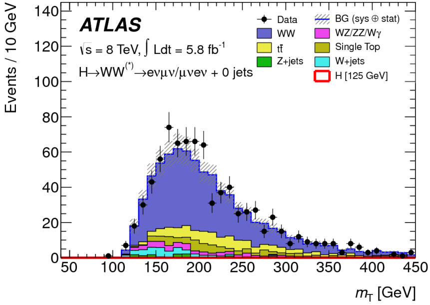
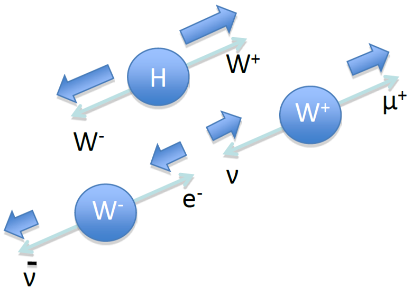
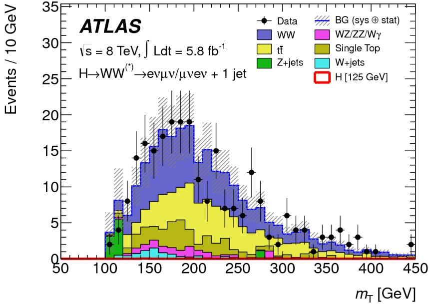




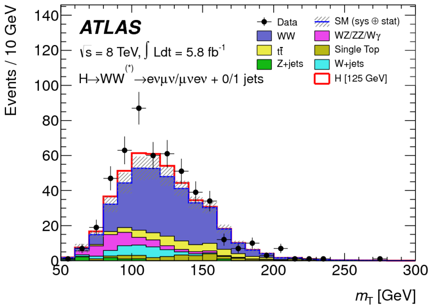


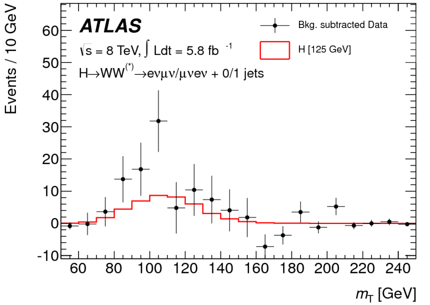
$H \to WW \to l\nu l\nu$: signal region

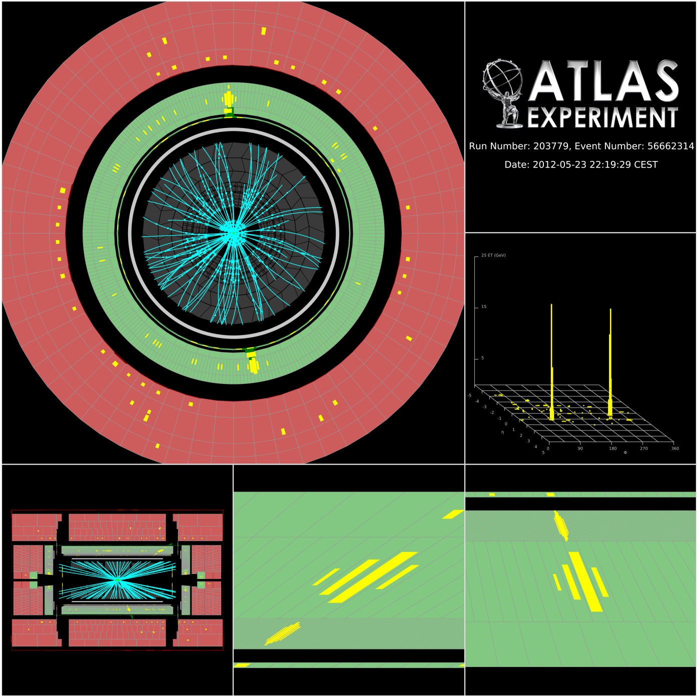
- Table shows number of expected signal and background events and observed data events for: $0.75 \cdot m_H < m_T < m_H$ for $m_H = 125\ GeV$
- An excess of events is observed relative the background expectation

$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left|\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

	0-jet	1-jet	2-jet
Signal	20 ± 4	5 ± 2	0.34 ± 0.07
WW	101 ± 13	12 ± 5	0.10 ± 0.14
$WZ^{(*)}/ZZ/W\gamma^{(*)}$	12 ± 3	1.9 ± 1.1	0.10 ± 0.10
$t\bar{t}$	8 ± 2	6 ± 2	0.15 ± 0.10
$tW/tb/tqb$	3.4 ± 1.5	3.7 ± 1.6	–
$Z/\gamma^* + \text{jets}$	1.9 ± 1.3	0.10 ± 0.10	–
$W + \text{jets}$	15 ± 7	2 ± 1	–
Total background	142 ± 16	26 ± 6	0.35 ± 0.18
Observed	185	38	0







$H \to \gamma\gamma$

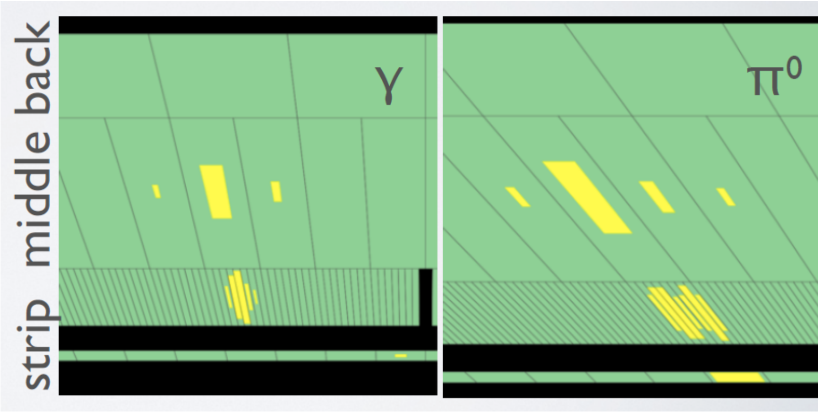
$\sigma \approx 0.05\ pb$

$\approx$ 300 signal events produced in 5.8 fb^{-1} at 8 TeV

ggF: 87%
VBF: 7%
W/ZH: 5%

$m^2_{\gamma\gamma} =$
$2E_1E_2(1 - cos\alpha)$

$H \to \gamma\gamma$: photon identification

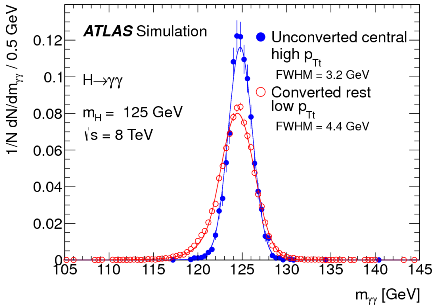


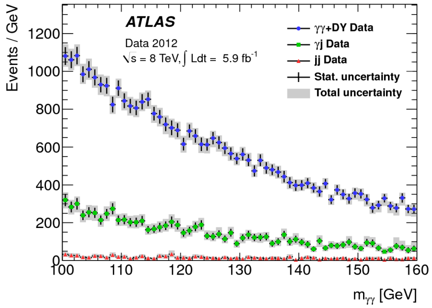
- Fine η granularity in the strip layer to reject π^0
- EM shower shape to reject fake photons from jets $\approx O(8000)$ jet rejection 85% photon efficiency
- Longitudinal segmentation to measure shower direction and to improve energy measurement

$H \to \gamma\gamma$: analysis strategy

- Two isolated photons with $p_T > 40, 30$ GeV
- Search for a narrow mass peak in di-photon mass spectrum
- Requires excellent EM energy resolution
- Split events in 10 categories to optimize signal/background
- Irreducible SM backgrounds are fitted from sidebands
  - Background composition measured from data (for cross-checks)

$\gamma\gamma$	$j\gamma$	jj
$80 \pm 4\%$	$19 \pm 3\%$	$1.8 \pm 0.5\%$

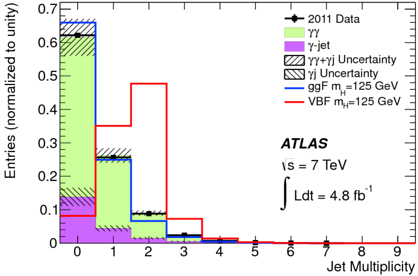


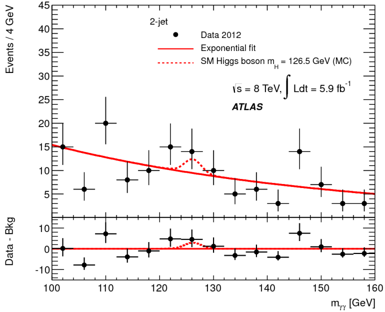


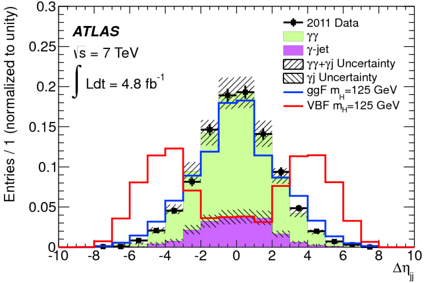
$H \to \gamma\gamma$: 2-jet channel

- Exclusive 2-jet VBF category
- VBF topological cuts:
  - $|\Delta\eta_{jj}| > 2.8$
  - $m_{jj} > 400\ GeV$
  - $\Delta\phi(\gamma\gamma, jj) > 2.6$
- VBF process is 70% of signal events

	N_{sig}	N_{data}
8 TeV	3.0	139
7 TeV	2.2	89

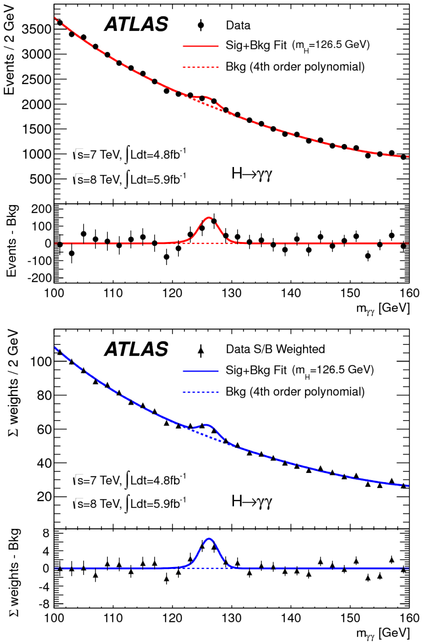






$H \rightarrow \gamma\gamma$

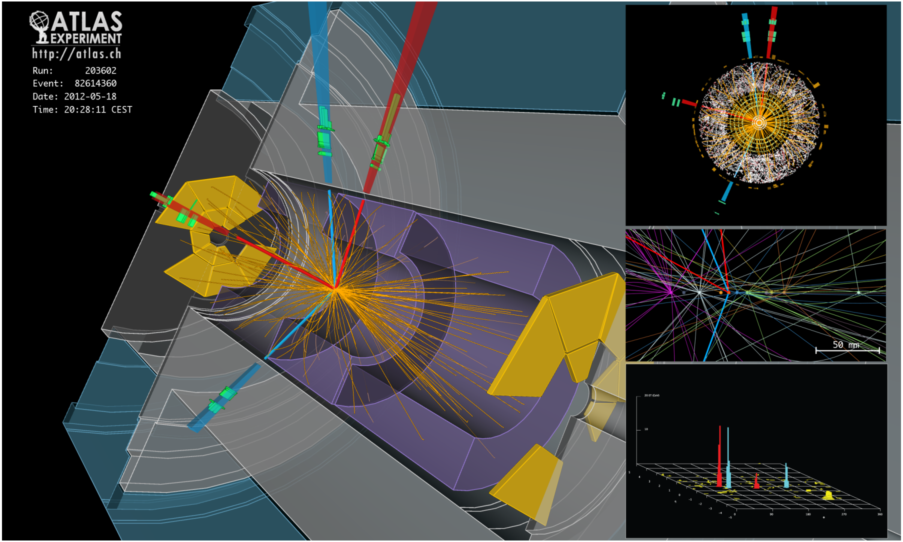
- An excess of events observed at $m_H = 126\ GeV$
- Fit $m_{\gamma\gamma}$ spectrum in each of 10 categories
- Fit signal with Crystal Ball + Gaussian
- Fit background using one of two functions:
    - 4th degree Bernstein polynomial
    - Exponential of 2nd degree polynomial
- Functions optimized to reduce potential bias and retain good statistical power using simulated events
- Weighted distribution with weight wi for category i defined as $ln(1 + Si/Bi)$



$H \to ZZ \to 4l$

$$\sigma(m_H = 125\ GeV) \times B \approx 3\ fb$$

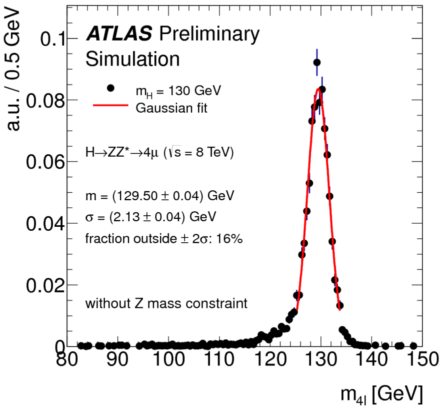
$\approx$ 16 signal events produced in 5.8 fb^{-1} 8 TeV



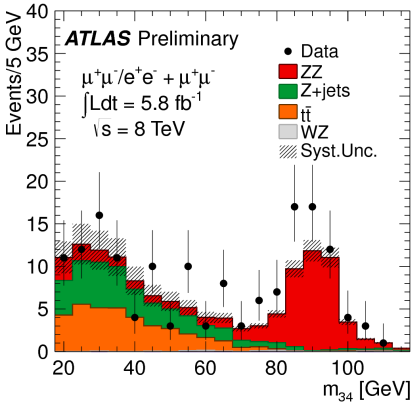
$H \to ZZ \to 4l$: analysis strategy

- Four isolated electrons or muons with $p_T > 20, 15, 10, 7 - 6(e - \mu)$ GeV
- $50 < m_{12} < 105$ GeV, $m_{34} > 17.5 - 50$ GeV
- Search for a narrow mass resonance
- 3 event (resolution) categories: $4e$, $2e2\mu$, 4μ
- Irreducible SM $ZZ^* \to 4l$ background - estimated from simulation
- Reducible Z+jets and $t\bar{t}$ backgrounds - estimated from data

4μ : $\sigma = 2.1$ GeV



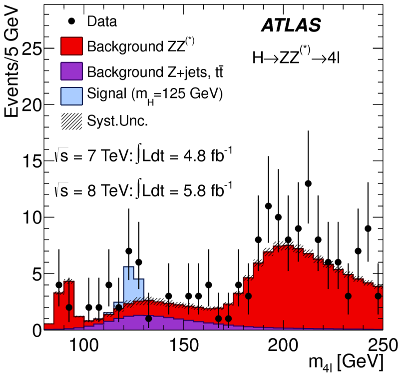
Relax impact parameter for $Z + \mu\mu$

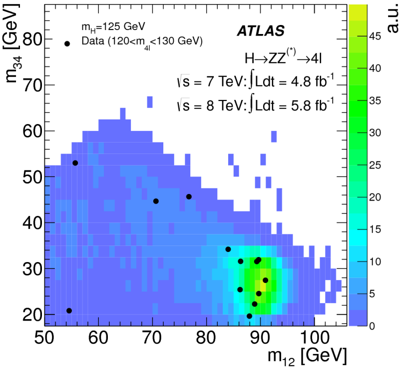


$H \to ZZ \to 4l$: four-lepton invariant mass

- Observe an excess of events near $m_{4l} = 125\ GeV$
- A number of selected candidate events $115 - 135\ GeV$ range:

	Signal	$ZZ^{(*)}$	$Z+$jets, $t\bar{t}$	Observed
4μ	2.09 ± 0.30	1.12 ± 0.05	0.13 ± 0.04	6
$2e2\mu/2\mu2e$	2.29 ± 0.33	0.80 ± 0.05	1.27 ± 0.19	5
$4e$	0.90 ± 0.14	0.44 ± 0.04	1.09 ± 0.20	2





Statistics tools and techniques

- Likelihood function:
  $\mathcal{L}(data|\mu,\theta) =$
  $\text{Poisson}(data|\mu \cdot s(\theta) + b(\theta)) \cdot p(\tilde{\theta}|\theta)$

  data - experimental observation
  θ - systematics nuisance parameters
  s - number of signal events
  b - number of background events
  μ - signal strength

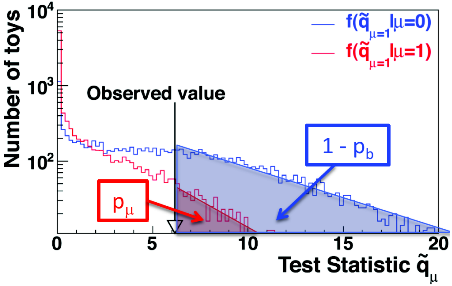
- 95% confidence limit for exclusion limits:
  $CL_s(\mu) = \frac{p_\mu}{1-p_b}$
  Adjust μ until $CL_s = 0.05$

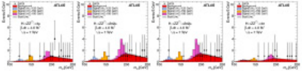
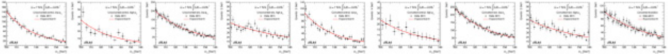
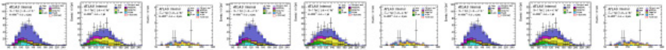
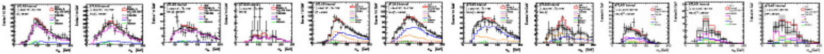
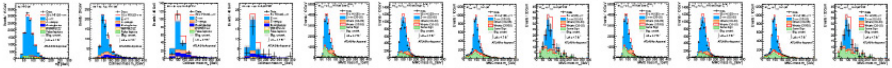
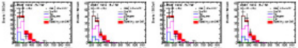
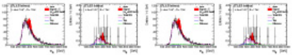
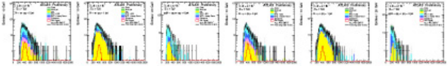
- p_0 tests the background only hypothesis:
  $\tilde{q}_0 = -2ln\frac{\mathcal{L}(data|0,\hat{\theta}_\mu)}{\mathcal{L}(data|\hat{\mu},\hat{\theta})}$

- p_0 - probability that the background could reproduce (fluctuates into) the same excess of events

- Profile likelihood ratio:
  $\tilde{q}_\mu = -2ln\frac{\mathcal{L}(data|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data|\hat{\mu},\hat{\theta})}$, $0 \geq \hat{\mu} \geq \mu$

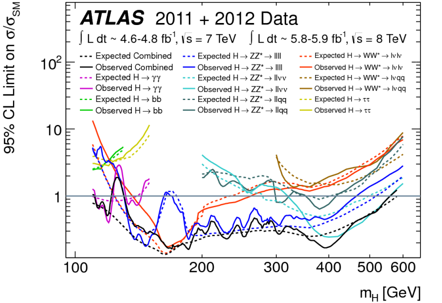
  $\hat{\mu},\hat{\theta}$ - maximize $\mathcal{L}$
  $\hat{\theta}_\mu$ - maximize $\mathcal{L}$ for given μ

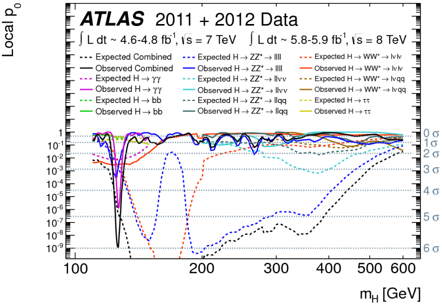


Combined results

- The SM Higgs boson is excluded at 95% CL in the mass range: 111-122 GeV and 131-559 GeV
- Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4\ \mathrm{(stat)}\ \pm 0.4\ \mathrm{(sys)}\ \mathrm{GeV}$
- Local significance of 5.9σ, corresponding to a background fluctuation probability of 1.7×10^{-9}
- Global signficance of 5.1σ for $110\ GeV < m_H < 600\ GeV$
- Compatible with the production and decay of the SM Higgs boson





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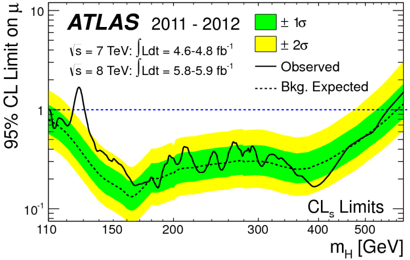
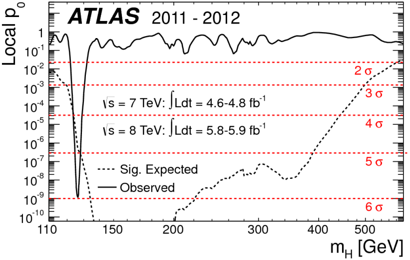
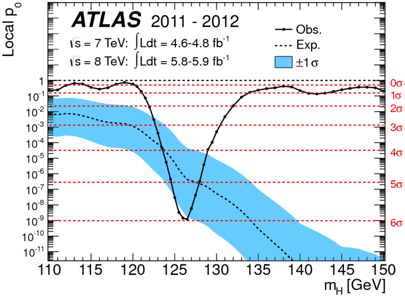
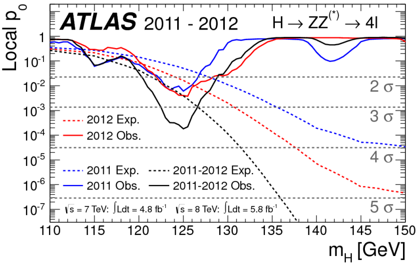
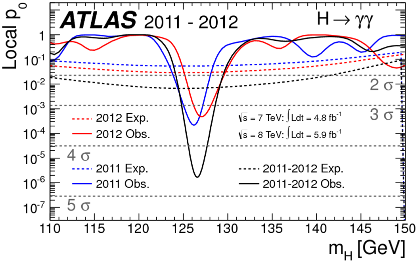


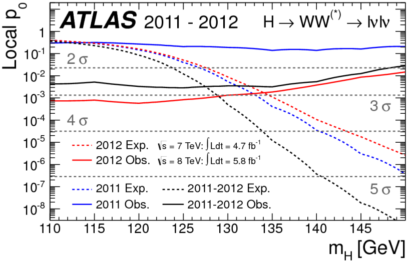


Higgs results



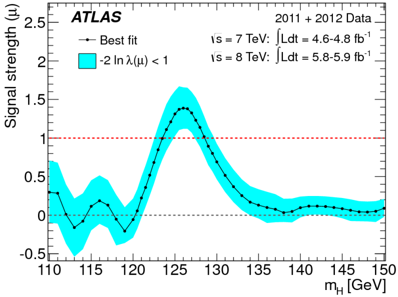


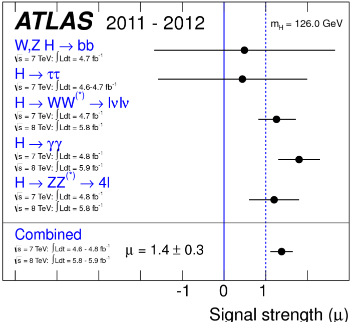


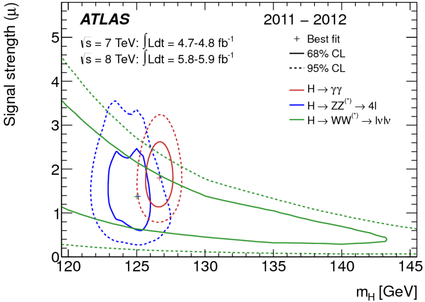


Signal strength and mass

- The observed excess corresponds to $\hat{\mu} = 1.4 \pm 0.3$ for $m_H = 126\ GeV$, consistent with the SM Higgs hypothesis $\mu = 1$
- The probability for a single Higgs boson-like particle to produce resonant mass peaks in the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels separated by more than the observed mass difference, allowing the signal strengths to vary independently, is about 8%

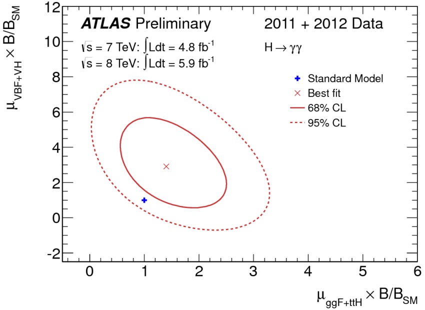


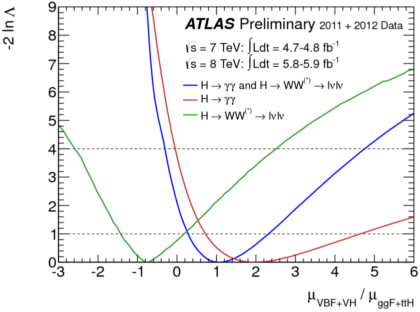


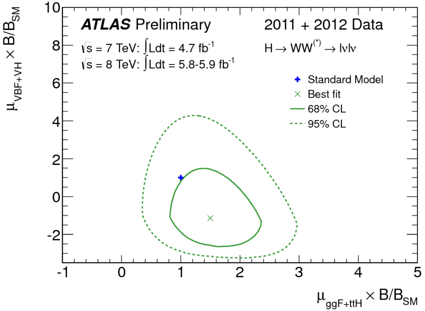


Higgs production signal strength: $\mu_{VBF+VH}, \mu_{ggF+ttH}$

- $m_H = 126\ GeV$
- μ_{VBF+VH} scale with WH/ZH couplings
- $\mu_{ggF+ttH}$ scale with ttH coupling
- Decay branching ratios cancel for this ratio: $\mu_{VBF+VH}/\mu_{ggF+ttH}$
- Model independent way to test compatibility of production mechanisms with the SM prediction







Standard Model Higgs boson

- Is the new mass resonance the Higgs boson predicted by the Standard Model?
- Experimental measurements of the Higgs properties:
  - Couplings: production cross-sections and branching ratios
  - Spin and CP
  - Higgs triple self coupling
  - Is there more than one mass state?
- Two approaches:
  - Test against specific theoretical models
  - Model independent searches for deviations from SM properties

Higgs coupling properties measurements: simplified framework

- LHC Higgs XS working group interim recommendations: arXiv:1209.0040
- The signals observed in the different search channels originate from a single narrow resonance with a mass of 126 GeV. The case of several, possibly overlapping, resonances in this mass region is not considered.
- The width of the Higgs boson with a mass of 126 GeV is assumed to be negligible:

$$\sigma \times BR(ii \to H \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$

- Only modifications of couplings strengths, i.e. of absolute values of couplings, are taken into account, for example:

$$(\sigma \times BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \times BR_{SM}(H \to \gamma\gamma) \times \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

- The tensor structure of the Higgs couplings is assumed to be the same as in the SM. This means that the observed state is assumed to be a CP-even scalar.
- Measurements of Higgs spin and CP properties require dedicated analyzes since kinematics distributions are modified under non-SM assumption

Higgs production and decay parameters

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_W^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_Z^2$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma_{\mathrm{t\bar{t}H}}^{\mathrm{SM}}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma_{\mathrm{WW}^{(*)}}^{\mathrm{SM}}} = \kappa_W^2$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_Z^2$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{b\bar{b}}}^{\mathrm{SM}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_\tau^2$$

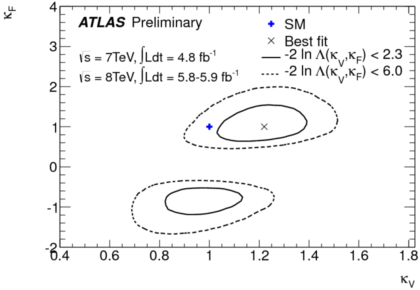
$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

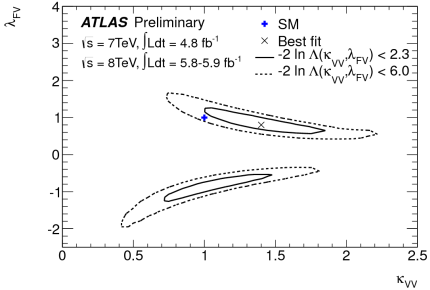
Higgs decays to fermions and bosons: κ_F, κ_V

- $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$
- $\kappa_V = \kappa_W = \kappa_Z$

Assuming only SM contributions to Γ_H



No assumptions on total width



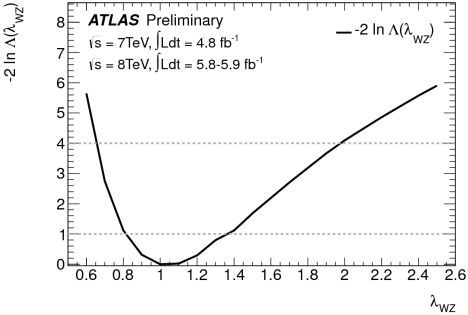
- Allow non SM contributions to Γ_H:
  - $\lambda_{FV} = \kappa_F / \kappa_V$
  - $\kappa_{VV} = \kappa_v \cdot \kappa_V / \kappa_H$

$-2 ln\Lambda < 2.3(6.0)$ correspond typically to 68% and 95% CL

Probing the W and Z couplings

- Three free parameters:
  - $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$
  - κ_W
  - κ_Z
- $\lambda_{WZ} = \kappa_W / \kappa_Z = 1.07^{+0.35}_{-0.27}$
- The VBF process is parametrized as the function of κ_W and κ_Z predicted by the SM

No assumptions on total width

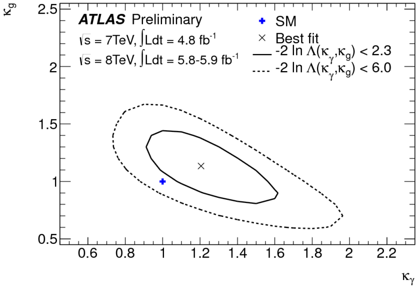


Probing non-SM contributions

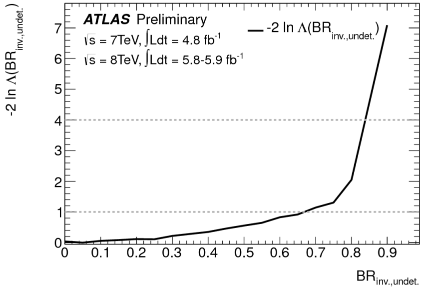
Test for non-SM contributions to $gg \to H$ and $H \to \gamma\gamma$ loops:

- Modify $gg \to H$ production: κ_g
- Modify $H \to \gamma\gamma$ decays: κ_γ
- Fix all other couplings to SM values: $\kappa = 1$

Assuming only SM contributions to Γ_H



No assumptions on total width

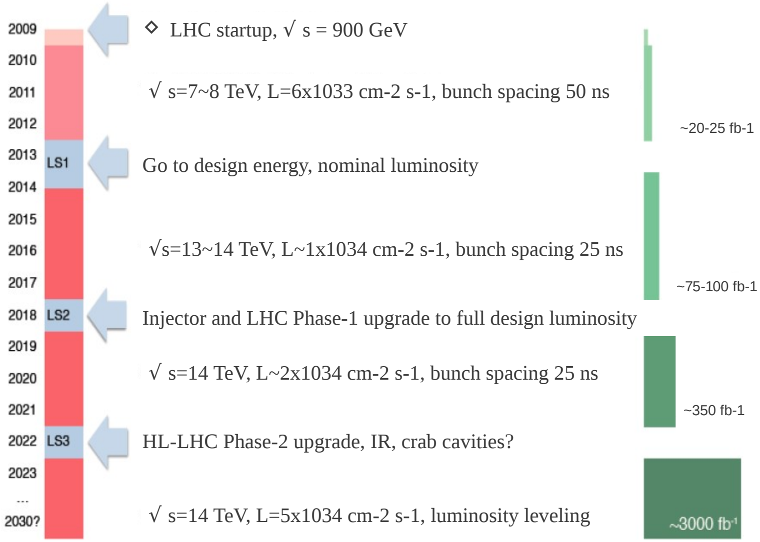


- Allow Higgs decays to undetected particles:

$$\Gamma_H = \frac{\kappa_H(\kappa_i)}{(1-BR_{undetec.})} \times \Gamma_H^{SM}$$

- $BR_{undetec.} < 0.84$

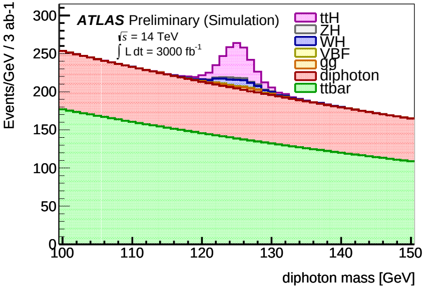
(Assumed) LHC schedule



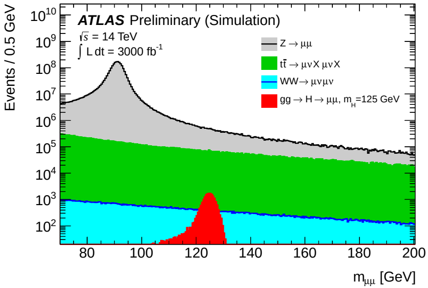
Higgs physics at a High Luminosity LHC with ATLAS

- Additional channels targeted for high luminosity LHC with $\sim 3000\ fb^{-1}$
- Realistic assumptions regarding upgraded detector performance with up to ~ 140 collisions per crossing
- Direct measurement of ttH in di-photon channel
- Measurement of Higgs coupling to 2nd generation fermions via $H \rightarrow \mu\mu$

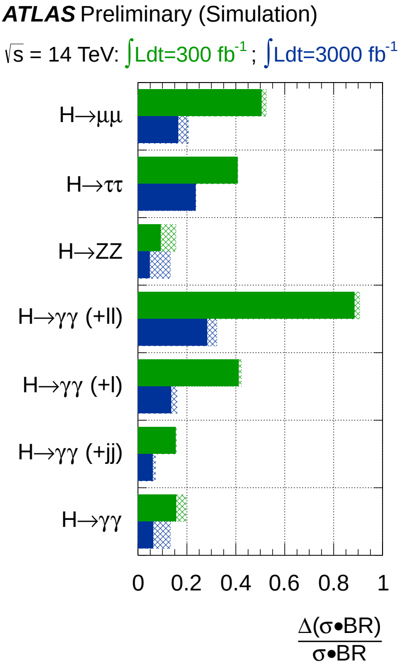
$gg \rightarrow ttH \rightarrow 1\ lepton + jets + \gamma\gamma$



$gg \rightarrow H \rightarrow \mu\mu$



- Estimates of precision for measurements of SM Higgs branching ratios with 300 fb^{-1} and 3000 fb^{-1}
- Order 10-20% precision for ggF and VBF production in $H \to \gamma\gamma$
- Addition of associate production (ZH and WH) channels is expected to improve these results considerably
- With 300 fb^{-1} at 14 TeV the spin/CP quantum numbers of non-mixed states can be measured at $5\,\sigma$ level
- With 300 fb^{-1} at 14 TeV $HH \to b\bar{b}\gamma\gamma$



Congratulations to CERN for the fantastic LHC performance!

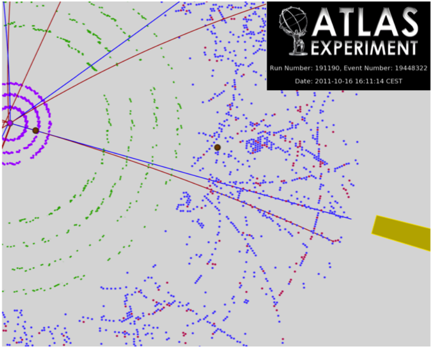
- Impressive performance by the ATLAS experiment in all aspects: detector design and construction, detector performance and calibration, data taking efficiency and data quality, simulation and physics results
- Clear evidence for the production of a neutral boson with a measured mass of 126.0 $\pm 0.4\ (\mathrm{stat})\ \pm 0.4\ (\mathrm{sys})\ \mathrm{GeV}$
- Compatible with the production and decay of the Standard Model Higgs boson
- A program of precision measurements of properties of the new particle
- Already recorded 15 fb^1 - more results in pipeline: Higgs properties, precision Standard Model measurements and searches for new physics

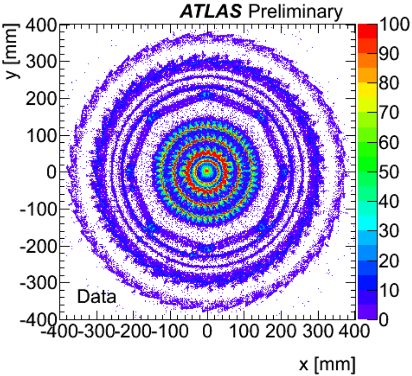
Thank you and stay tuned!

BACKUP

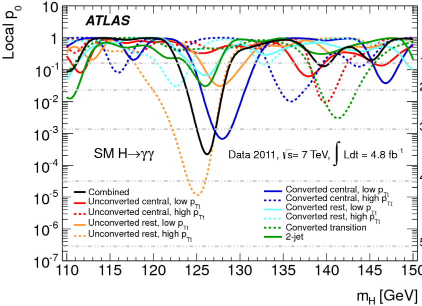
$H \rightarrow \gamma\gamma$: photon conversion

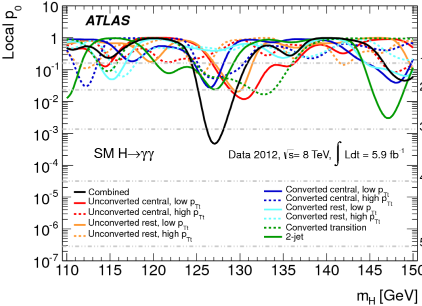
- Photons convert into electron and positron pairs in the tracker material
- Reconstruct as displaced Inner Detector track(s) matched to electromangetic cluster
- Measure amount of Inner Detector material with conversion vertex density
- 52% of signal events contain at least one converted photon
- Uncertainty on event migration between converted/unconverted is 4%

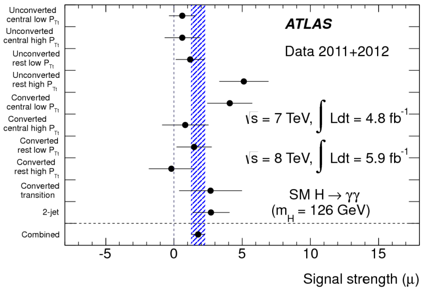


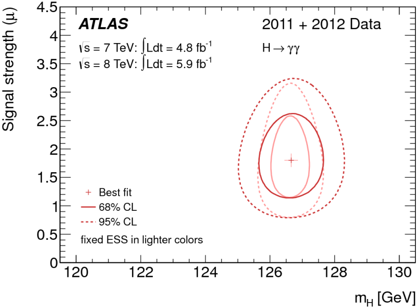


$H \to \gamma\gamma$: categories

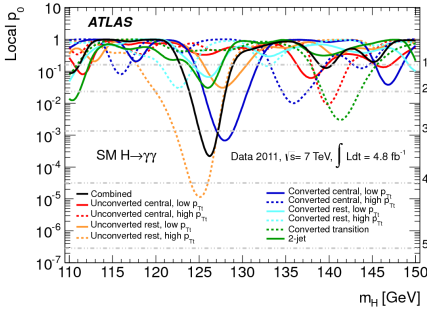


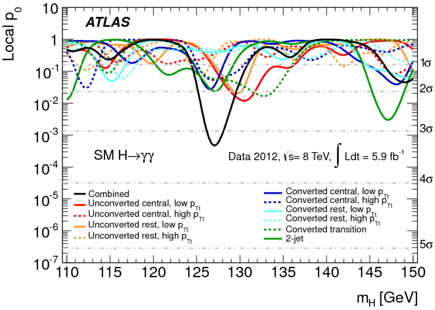


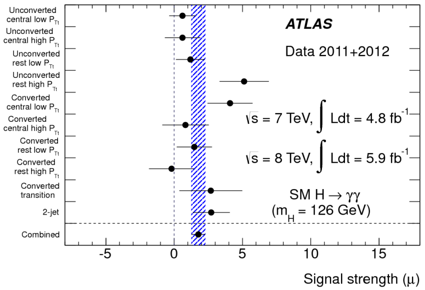


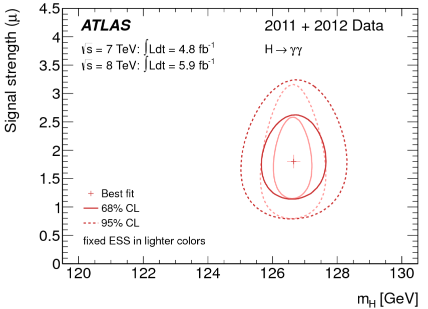


$H \to \gamma\gamma$: categories

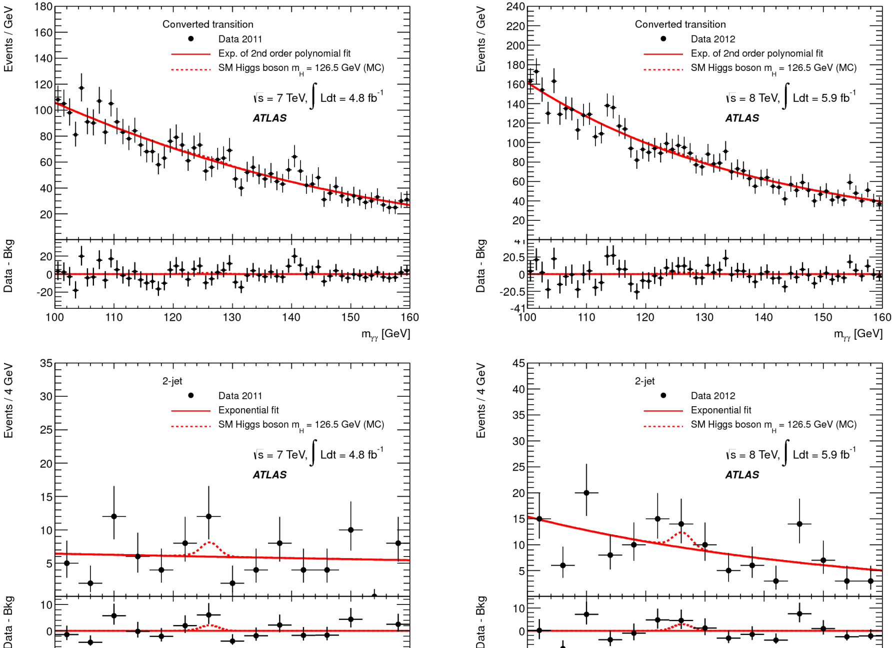




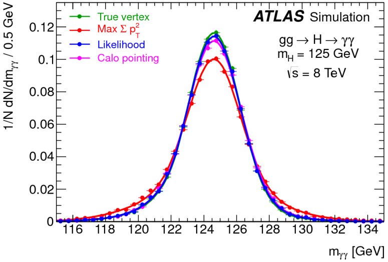


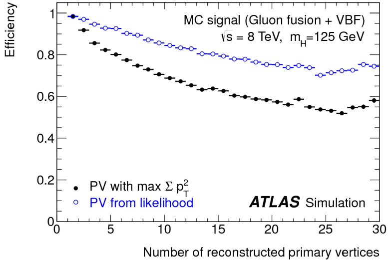


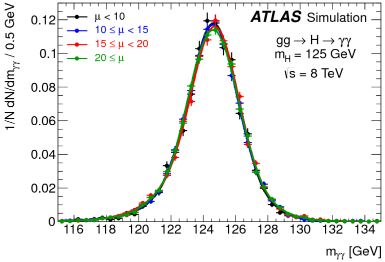
$H \to \gamma\gamma$

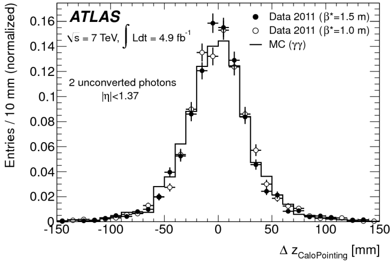


$H \rightarrow \gamma\gamma$





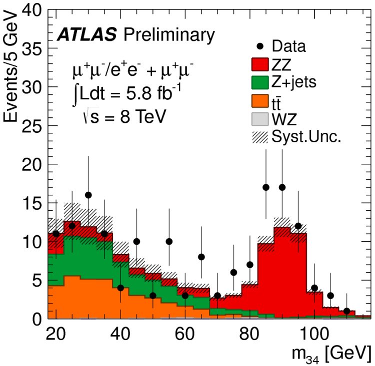




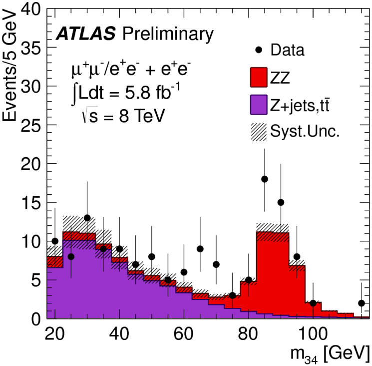
$H \to ZZ \to 4l$: backgrounds

- Normalize $ZZ^{(*)}$ from simulation
- Normalize reducible backgrounds from control regions
  - Z+jets background - relax lepton selection cut
  - $t\bar{t}$ - $e\mu$ channel
  - Z+jets background validation - relax impact parameter and isolation

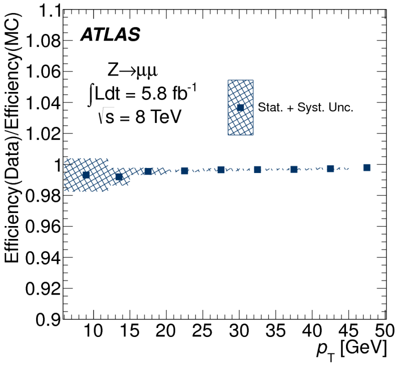
Relax impact parameter for $Z + \mu\mu$



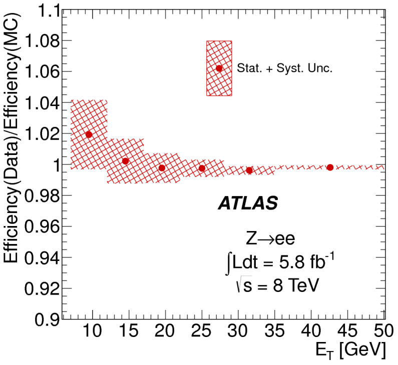
Relax isolation cut for $Z + ee$



$H \to ZZ \to 4l$

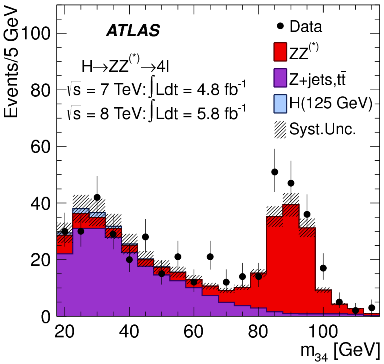


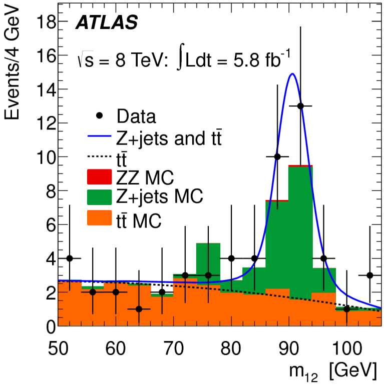
ATLAS
Z→μμ
∫Ldt = 5.8 fb^-1
√s = 8 TeV
Stat. + Syst. Unc.
Efficiency(Data)/Efficiency(MC)
p_T [GeV]

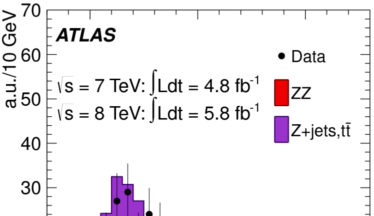


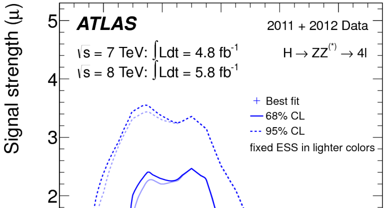
ATLAS
Z→ee
∫Ldt = 5.8 fb^-1
√s = 8 TeV
Stat. + Syst. Unc.
Efficiency(Data)/Efficiency(MC)
E_T [GeV]

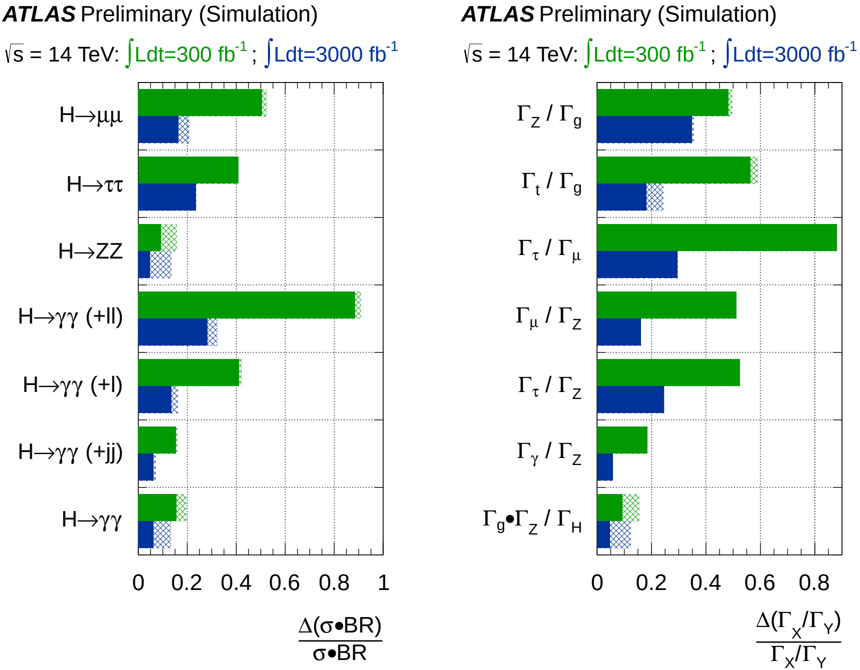
$H \to ZZ \to 4l$


ATLAS
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Data
ZZ(*)
Z+jets,tt̄
H(125 GeV)
Syst.Unc.
Events/5 GeV
m34 [GeV]
0
20
40
60
80
100
20
40
60
80
100


ATLAS
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Data
Z+jets and tt̄
tt̄
ZZ MC
Z+jets MC
tt̄ MC
Events/4 GeV
m12 [GeV]
0
2
4
6
8
10
12
14
16
18
50
60
70
80
90
100


ATLAS
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Data
ZZ
Z+jets,tt̄
a.u./10 GeV
30
40
50
60
70


ATLAS
2011 + 2012 Data
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
H → ZZ(*) → 4l
Best fit
68% CL
95% CL
fixed ESS in lighter colors
Signal strength (μ)
2
3
4
5



ATLAS Preliminary (Simulation)
$\sqrt{s}$ = 14 TeV: $\int Ldt$=300 fb^{-1} ; $\int Ldt$=3000 fb^{-1}
H→μμ
H→ττ
H→ZZ
H→γγ (+ll)
H→γγ (+l)
H→γγ (+jj)
H→γγ
0
0.2
0.4
0.6
0.8
1
$\frac{\Delta(\sigma \bullet BR)}{\sigma \bullet BR}$
ATLAS Preliminary (Simulation)
$\sqrt{s}$ = 14 TeV: $\int Ldt$=300 fb^{-1} ; $\int Ldt$=3000 fb^{-1}
Γ_Z / Γ_g
Γ_t / Γ_g
Γ_τ / Γ_μ
Γ_μ / Γ_Z
Γ_τ / Γ_Z
Γ_γ / Γ_Z
$\Gamma_g \bullet \Gamma_Z / \Gamma_H$
0
0.2
0.4
0.6
0.8
$\frac{\Delta(\Gamma_X/\Gamma_Y)}{\Gamma_X/\Gamma_Y}$